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Challenges for Frequency-Reconfigurable Antennas in Small Terminals

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***Abstract*—This paper gives an overview of the techniques published over the past years to address continuous frequency tuning. It presents the challenges that have been encountered and relates to each other the parameters that influence the losses of the resulting antenna structure. A mock-up is made with a PIFA and a packaged RF-MEMS tunable capacitor to measure its efficiency as the resonance is tuned towards the LTE-700 band.**

Keywords—Tunable circuits and devices; Patch antennas; Capacitors; Antenna measurements; Reconfigurable architectures; Tuning.

I. Introduction

For the 4^{th} Generation (4G) of mobile communications the Long Term Evolution (LTE) standard requires the mobile terminals to operate in a significant amount of bands and a very wide range of frequencies. This is to say the handsets should be able to cover 24 different bands and all the frequencies from 700 MHz up to 2.7 GHz, which corresponds to the bands 12 and 7 [**?**]. Multi-band antennas have been largely used in the mobile phone industry in order to cover more than one band simultaneously. Their relatively easy-to-integrate structure and their low cost made them very attractive for antenna engineers. Nevertheless the ever increasing number of bands to cover, lower frequencies being part of the spectrum and the trend for smaller platforms reaches the limits of multi-band antennas integration. Additionally the implementation of Multiple-Input Multiple-Output (MIMO) systems will increase the number of antennas required on the platform. For the small handsets the main constraint is the space available.

As an alternative to multi-band antennas Frequency-Reconfigurable Antennas (FRA) - also called tunable antennas - have been investigated in order to provide maximum connectivity. FRA offer the possibility to dynamically change the resonance frequency of the antenna through electrical means. The space consumption is greatly reduced for FRA as one single resonant element can be used to cover all the bands. Furthermore this element is designed for its highest targeted band of operation which results in small size elements [**?**]. In addition to smaller elements, size reduction in the RF chain can be achieved by passing some of the filter requirements on a narrow-band antenna design.

This paper, besides giving an overview of the tuning methods published in the recent years, presents the challenges that can be met during design and fabrication processes of an FRA, from an efficiency point of view. This paper is structured in six sections. The common techniques for antenna tuning are introduced in Section II. Successively Section III describes the trade-offs to consider at a design stage of an FRA. This is followed in Section IV by challenges of the integration of the tuner within the FRA structure. A prototype antenna is built and measured with packaged MEMS capacitors in Section V. Conclusions end the paper in Section VI.

II. Tuning Techniques for Antennas in Small Terminals

Typical applications of FRA can be divided into two categories, the antennas that aim at switching between distinct frequency bands, or the antennas that aim at providing continuous tuning within - or between - operating bands and standards. The latter ones are of most interest as they will provide the maximum connectivity required for 4G.

Additionally, their coverage requirement can be reduced to the bandwidth of a channel, as opposed to a full band. And the system design will benefit from a narrow-band antenna design, as it can have a filtering function which will relax the requirements on the filters themselves and provide a great size and cost reduction in the RF chain.

Continuous tuning - also called fine-tuning - is commonly achieved using tunable substrates or tunable components. On the one hand, the tunable substrates have the ability to vary their relative permittivity or permeability, which modifies the effective electrical length of the antenna, hence its operating frequency. Some examples are given in [**?**]-[**?**]. The main drawbacks of this technique are the fairly high electrical conductivity created - as high loss tangent of the substrate can severely degrade the efficiency of the antenna - and the limitations in achieving uniform films for planar structures. On the other hand, the tunable components are easier to physically integrate in the small antennas structure and are the focus of this paper. They are built based on electrically controlled reactances (usually capacitances) that can take a linear range of values in order to achieve smooth variations in the overall reactance of the antenna, and the resonance frequency.

Different techniques for continuous tuning using tunable components found in the literature will be summarized and compared in the following section. One of them will be chosen for the FRA presented in this paper.

A. Literature Examples

The components used for continuous tuning can be divided into three groups: the varactors, the PIN diodes or Field Effect Transistor (FET) and the RF Micro-Electro-Mechanical (MEMS). Examples of the integration of such components in Electrically Small Antennas (ESA) are presented.

1) Varactors: Varactors - also known as variable capacitor diodes or varicaps - can vary the resonance frequency of an antenna by providing different capacitance values in function of the bias applied across the diode. For instance, in [**?**] a variable capacitor is placed between a Planar Inverted-F Antenna (PIFA) and its Ground Plane (GP) at a fixed distance from the feed. With a range of capacitances between 3 and 20 pF, the inherently narrow-band radiator can reach an effective bandwidth of 10 % around 900 MHz. A similar example on a patch antenna is shown in [**?**] with a tuning range up to 15% around 2.2 GHz, or on a dual-band slot antenna in [**?**] and [**?**] where the tuning range is above 1.2 GHz and efficiencies vary from 92% to 58 %.

2) PIN diodes and FET: Tuning components based on semiconductor switches are mainly PIN diodes and reactive FET. The main use of PIN diodes is switching between bands though, and fine-tuning within the band is further achieved with a varactor, as in [**?**] for frequencies between 2 and 5 GHz. Continuous tuning with only PIN diodes requires many of them for widely FRA, leading to an increased complexity of the structure and low switching efficiency. The use of FET in [**?**] provides a 10% tuning range around 10GHz. In [**?**] tuning over the GSM-900 band is shown, at the expense of 24% reduction in the efficiency. Indeed the high insertion loss [**?**] is the main drawback of this method.

3) RF-MEMS: More recent tuning techniques include RF-MEMS capacitors on patch antennas, as in [**?**] that shows tuning between 15 GHz and 16 GHz and in [**?**] that shows the integration of the RF-MEMS in a slot within the patch structure and tuning in the 1.5 GHz band. The main advantage of MEMS switches over semiconductor switches is their higher efficiency, which can be a result of galvanic contact in the on-sate for some components, or a result of a constant equivalent resistance in purely capacitive MEMS - as the one chosen for the prototype presented in the following sections.

B. Proposed Design

The selected tuning technique for the proposed design is RF-MEMS capacitors. The frequencies of interest will be below 1GHz as they are the most challenging for small platforms, as a result of resonance frequencies below the GP resonance. A dual-band low-profile patch antenna will be prototyped and an RF-MEMS tunable capacitor will be integrated in its structure in order to tune its low band from GSM-900 to LTE-700.

III. Design Trade-offs

Investigation of the tuning range, tuning resolution and the consequences on the bandwidth (BW), Quality factor (Q) and efficiency will be shown in this section.

A. Too High Quality factor (Q)

It is well know that the GP has a major function in the radiation mechanism of ESA. For typical mobile phone form factors, the resonance frequency of the GP is about 1 GHz. The Q of the radiating structure is the lowest when the antenna is designed to have the same resonance frequency as the GP [**?**]. As the resonance frequency of the antenna element is tuned further away from the GP resonance, the Q of the structure increases dramatically. This phenomenon leads to an inversely proportional reduction of the bandwidth [**?**], [**?**]. The main issues arising with a very high Q are:
- the bandwidth may be too narrow to cover one channel,
- tuning becomes coarser,
- the radiation efficiency may be below the acceptable threshold.

Consequently covering the low frequencies extending the tuning range is a major challenge.

B. Narrow Bandwidths

Depending on the Q of the original antenna design - without the tuner - and on the tuning range, the Q of the FRA at its lowest frequency will be very high. This phenomenon results in narrow bandwidths for frequencies as low as 700 MHz (band 12 of LTE standard). FRA only need to cover one channel, which varies in LTE from 1.4 MHz to 20 MHz [**?**].

C. Fine-tuning

To comply with the 4G standards using FRA antennas, not only the tuning range must be very wide but also every single band and channel between 700 MHz and 2.7 GHz must be covered with an acceptable level. Using varicaps for instance, the tuning step that can be reached with one capacitance stage is dependent on the amount of current that goes through the varicap. There is a first trade-off between the position of the varicap and the tuning step [**?**]. When the location of the tuning component is fixed, a step in increasing its reactance means a shift in frequency. This shift is constant over the tuning range but the bandwidth is not since the antenna Q increases. Fine-tuning is not possible anymore when the bandwidth gets too narrow to cover the immediate next channel. There is a second trade-off between the position of the varicap and the feasability of the design as currents and voltages at a given position can be very high and need to be handled by the varicap [**?**], losses should also be minimized.

D. Poor Matching

The antenna designers must aim for a structure covering every single frequency of the 4G radio spectrum with a Voltage Standing Wave Ratio (VSWR) at least equal to 3. However the antenna impedance is not constant throughout the tuning stages. A loss-less simulation of an FRA will show a degrading

matching as the operationg frequency it tuned far away from the original resonance frequency. This phenomenon can be observed in the Section **??**. The mismatch efficiency being a part of the total efficiency of the antenna system, it is partly responsible of the performance deterioration of FRA. This parameter is an additional constraint to reaching a wide tuning range. Tuning matching networks can be added, at the expense of losses in the total efficiency.
The challenges that need to be dealt with while tuning towards LTE-700 frequencies are the Q increase, the BW degradation, the coarser tuning resolution and the matching to the 50 Ω feed line degradation. Optimization with the tuning component location and the antenna geometry can lead to a successful design.

IV. Integration of the Tuner

Implementations of packaged MEMS switches in FRA antennas are carried out in [**?**] and [**?**] where practical aspects involved are explained. Assembling the FRA showed that additional modifications needed to be done to the packaged components in order to reduce a severe impedance mismatch. Further adjustments had to be done to the antenna in order to include bias networks and utilize the RF ground plane as a shared DC power plane. The necessary post-design-modifications of both elements suggest that the MEMS and the antennas should be conceived throughout a joint fabrication process.
Tuning components are commonly placed between the radiating element and the ground plane, or within the radiating element itself. These locations usually result in significant losses since they are at high RF voltages and currents locations [**?**]. When selecting a tuning component to modify the resonance frequency of an antenna, particular attention should be paid to the additional losses it introduces, as it will degrade the total efficiency. Therefore the selection of the component should be done based on its Q value, which is function of its Equivalent Series Resistance (ESR). The insertion loss is used to rank the components. However it is given by the manufacturers in a 50 Ω environment, which is not the case when they are placed in the antenna structure. In [**?**] the insertion loss of a switch was measured 4 times higher than the one given by the manufacturers at the same frequency. This significant difference was due to the 10 Ω environment in which the switch was placed, close to the antenna feed point. In fact the power loss of the switch increases as the load resistance diverges from 50 Ω. In [**?**] the location of the integrated MEMS component lead to losses of 13 dB, even at high frequencies: 2 GHz. In an other example [**?**], the total efficiency of the MEMS reconfigurable antenna is below 50 % in the GSM-900 band and in the GSM-1800 band. Ways to artificially create an environment as close as possible to 50 Ω, in order to reduce the losses of the tuning component are presented in [**?**]. Shunt reactances between the antenna element and the tuner can be inserted without large additional losses, in order to modify the load resistance. MEMS are expected to meet the requirements on the component performances.

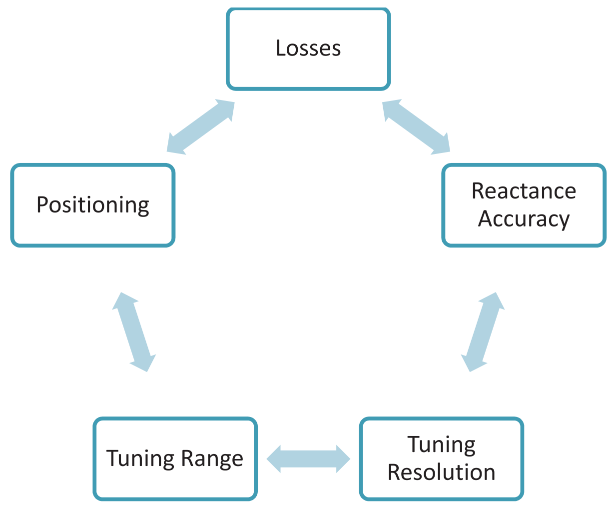

Fig. 1. Design trade-offs.

V. A prototype antenna

A. Antenna Design

The proposed antenna is a dual-band PIFA operating at the GSM bands. The prototype aims at fine-tuning the low-band resonance from the GSM-900 band to the band 14 of the LTE frequency spectrum with an RF-MEMS variable capacitor. These bands have been chosen because the low frequencies in small terminals are the most challenging. This is mainly for the required size at resonance compared to the available space, and because of a resonance significantly below the GP resonance. In the tuner [**?**] a range of capacitances varying between 0.125 pF (C1) and 1.875 pF (C2) - with 0.125 pF steps - is used. The location of the tuner on the antenna is chosen in order to optimize the tuning resolution with the capacitance steps. The tuner provides high performance and is implemented in contemporary phones, as Samsung Omnia [**?**]. It has a Q of 200 at 1 GHZ, a maximum signal voltage of 35 Volts and a self-resonance frequency at 5 GHz. The mocked-up antenna can be seen in Fig. **??** and is detailed in [**?**]. The tuner and the antenna share a common GP.
The antenna was first simulated in a Finite-Difference Time-Domain (FDTD) software. The initial resonance frequency of the antenna is 960 MHz and its simulated Q is 56 with a BW of 20 MHz. Adding the tuner to the mock-up, it was observed that the connection to the tuner - in its off-stage - shifts the resonance frequency to 890 MHz. Then, increasing the capacitance value of the tuner decreases the resonance frequency of the overall system. The system can be tuned until 790 MHz, where the simulated Q is 198 and its associated BW is 4 MHz. The magnitude of the reflection coefficient for the maximum and the minimum operating frequencies of the tuning range are plotted in Fig. **??**. The continuous tuning achieved by the prototyped antenna is shown in Fig. **??**. Good matching is shown in the measurements throughout the whole tuning range. Unlike the loss-less FDTD simulation, the measured antenna self-matches itself at the resonant frequency.

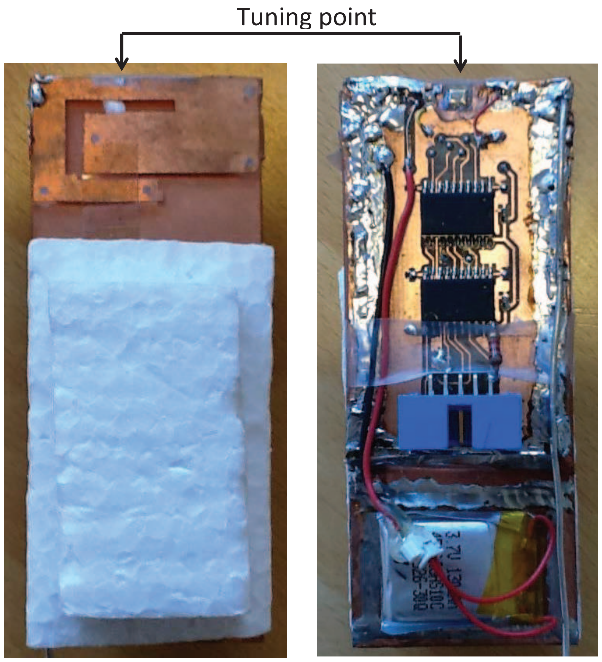

Fig. 2. Prototyped antenna.

This phenomenon is certainly due to the losses in the mock-up, which can also be seen in the very low reflection threshold (below -5 dB).

The Table **??** summarizes the evolution of the Q and the BW throughout the tuning range. These values are compared to the simulated values and depicted in Fig. **??**. The measured resonance frequencies match with the values from the simulation tool. It can be observed that the measured Q is lower than the simulated Q, and correspondingly the measured BW is larger than the simulated one. The difference in Q and BW are explained by the losses of the real mock-up. Indeed the FDTD simulation is done with Perfect Electric Conductor (PEC) elements for the antenna and the GP, and ideal capacitors for the tuner. In both simulation and measurements, the Q is dramatically increased - up to 141 in the measurements and the BW is decreased to 4 MHz. It can be seen in Fig. **??** that the Q of the system suffers dramatic discontinuities at three particular frequencies throughout the tuning range. This phenomenon is intrinsic to the Q calculation of narrow-band antennas as showed in [**?**] and comes from the circuitry chosen at the perfect matching step of the algorithm.

For the highest and the lowest bounds of the tuning range, the total efficiency (e_T) of the mock-up is measured in an anechoic chamber and calculated with 3-D integration technique. At 890 MHz e_T is -1.9 dB, whereas at 790 MHz e_T is -4.8 dB. Mismatch efficiency is negligible as the antenna self-matches itself. A degradation of 3 dB is explained by the increase in conductive losses at low frequencies. Further investigation is needed to identify precisely the cause of loss for the low LTE-700 band.

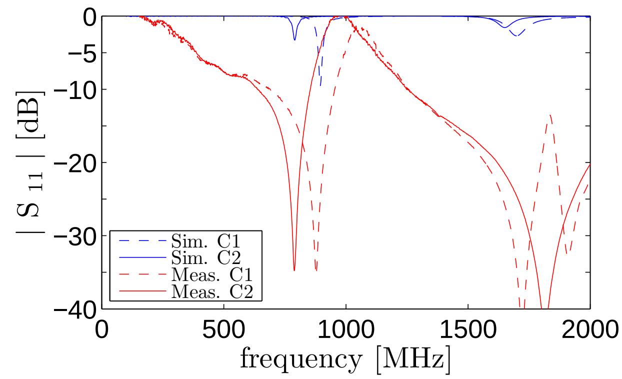

Fig. 3. Simulated (Sim.) and Measured (Meas.) $|S_{11}|$ parameter for the lowest and highest tuning stages, where C1=0.125 pF and C2=1.875 pF.

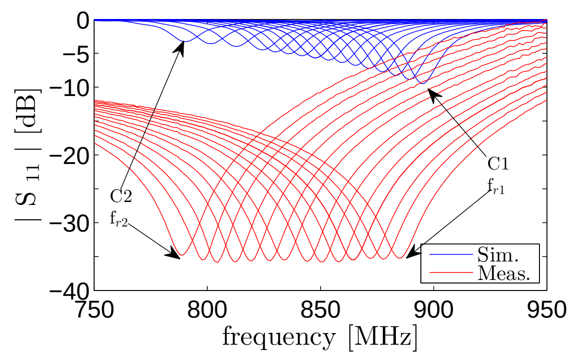

Fig. 4. Simulated (Sim.) and Measured (Meas.) $|S_{11}|$ parameter throughout its tuning range, between C1=0.125 pF and C2=1.875 pF.

TABLE I
Q AND BW OF THE MOCK-UP IN SIMULATIONS AND MEASUREMENTS

f_r [MHz]		**Q**		**BW [MHz]**	
sim.	**meas.**	**sim.**	**meas.**	**sim.**	**meas.**
890	891	89	79	10	11
884	883	88	94	10	9
878	878	110	94	8	9
866	870	108	93	8	9
861	863	108	115	8	7
855	855	143	114	6	7
849	846	142	113	6	7
843	840	141	112	6	7
831	831	139	111	6	7
825	823	206	110	4	7
814	816	204	109	4	7
802	801	201	107	4	7
791	793	198	141	4	6

VI. Conclusion

This paper has presented the challenges that can be met while manufacturing a FRA for 4G use. Having a wide and fine tuning range is a trade-off between the accuracy of the tuning component and its location. The dependency between the

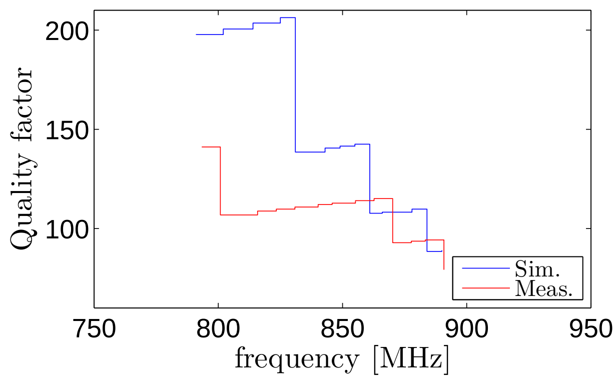

Fig. 5. Simulated (Sim.) and Measured (Meas.) Q of the prototyped antenna.

essential parameters of the FRA design are presented in order to understand the necessary trade-offs before manufacturing processes. Continuous tuning could be reached with an RF-MEMS variable capacitor (0.125 pF to 1.875 pF in 14 steps) between 890 MHz and 790 MHz. A frequency ratio f_R of 1.13 was achieved corresponding to a tuning range of 11 %. With higher values of the MEMS capacitor the tuning range can be increased to reach the band 12 of the LTE standard as the mock-up self-matches itself at resonance. However the Q of the antenna dramatically increases when the antenna is tuned towards lower frequencies, which results in narrower bandwidths, coarser tuning range, and poorer efficiency. The measured total efficiency dropped from -2 dB at 890 MHz to -5 dB at 790 MHz. The source of the losses must be further investigated, as it might come from multiple reasons: ESR, soldering tin or copper conductivity for example.

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